SULFATION IS RATE LIMITING IN THE FUTILE CYCLING BETWEEN ESTRONE AND ESTRONE SULFATE IN ENRICHED PERIPORTAL AND PERIVENOUS RAT HEPATOCYTES

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ABSTRACT:
The metabolic activities and tissue binding of estrone (E1) and estrone sulfate (E1S) on futile cycling were examined. Desulfation of E1S in the 9000g supernatant fraction (S9) of periportal (PP) and perivenous (PV) rat hepatocytes were of similar Vmax (E1S-E1) (2.9 ± 1.0 and 2.4 ± 0.9 nmol/min/mg of S9 protein), Km (E1S-E1) (30.4 ± 8.3 and 34.8 ± 6.6 μM), and desulfation intrinsic clearances (Vmax/E1S/Km (E1S-E1) of 77 and 55 μl/min/106 cells). The intrinsic clearance towards E1 sulfation (1 μM) in cytosolic preparations of PP hepatocytes was 4 times that of PV hepatocytes, fitting revealed that uptake of E1S (1484 and 1463 μl/min/106 cells) was rapidly and similar, and E1 sulfation was the slowest step in futile cycling. The greater metabolism of E1 in PV region led to higher levels of E1 and E1S in PP hepatocytes, and the nonlinear uptake, binding, and vesicular accumulation of E1S resulted in different t1/2 values for E1S and E1.

Estrone sulfate (E1S) is one of the compounds used in hormone replacement therapy. The activity of E1S results from the release of active estrone (E1) through desulfuration in liver, and E1 can be sulfated back to the inactive E1S. Typically, the rate of sulfation of E1 is measured, but the observation may be erroneously based on the net rate of formation of E1S. Since sulfoconjugation plays an important role in the deactivation and elimination of E1, it is critical to consider the roles of sulfation and desulfation on the duration of activity of E1S.

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1 Abbreviations used are: E1S, estrone sulfate; E1, estrone; E2, estradiol; E1G, estrone glucuronide; PV, perivenous; PP, periportal; PAPS, 3′-phosphoadenosine 5′-phosphosulfate; HPLC, high performance liquid chromatography; S9, 9000g supernatant fraction; rSULT1A1, 1.1) but not hydroxysteroid sulfotransferase (PV/PP ratio of 0.29 ± 0.21) nor phenol sulftotransferase (PV/PP ratio of 1.13 ± 0.23). Upon incubation of E1S (1–125 μM) with hepatocytes (30 min), higher concentrations of E1S and E1 were observed within PP than in PV cells, and saturation was evident at the higher concentrations. Based on the in vitro metabolic and tissue binding parameters for E1S and E1, and the published zonal uptake clearances of E1S (116 μl/min/106 cells) and E1 (1484 and 1463 μl/min/106 cells) by PP and PV cells was rapid and similar, and E1 sulfation was the slowest step in futile cycling. The greater metabolism of E1 in PV region led to higher levels of E1 and E1S in PP hepatocytes, and the nonlinear uptake, binding, and vesicular accumulation of E1S resulted in different t1/2 values for E1S and E1.

Estrone sulfate, a membrane-bound enzyme with a pH optimum of 7.4 is mainly responsible for the desulfuration of E1S and exhibits its highest activity in the liver (Milewich et al., 1984). Estrone sulfatase is also known as arylsulfatase C, a microsomal enzyme that copurifies with steroid sulfatase and cleaves the sulfate moiety of several 3-hydroxysteroid sulfates (Dolly et al., 1972). In female rats, an abundance of estrone sulfatase activity was found in both the endoplasmic reticulum and nucleus (Zhu et al., 1998). Previous studies suggest that desulfuration of 4-methylumbelliferyl sulfate by arylsulfatase C was homogeneous across the rat liver (Anundi et al., 1986) and human liver tissues (El Mouelhi and Kauffman, 1986).

The phenomenon of futile cycling between E1 and E1S has yet to be...
viewed in conjunction with hepatic transport of E₁ and E₁S and other metabolic pathways of E₁. Transport of E₁S in rat liver is found to be mediated by the organic anion-transporting polypeptides, Oatp1 (Jacquemin et al., 1994), Oatp2 (Noé et al., 1997), and Oatp4 (Cattori et al., 2000); the multispecific organic anion transporter 3, OAT3 (Kusuhara et al., 1999); and the sodium-dependent taurocholate-cotransporting polypeptide. Ntcp (Hagenbuch et al., 1991). The Kₘ values for the uptake of E₁S mediated by Oatp1 (Bossoy et al., 1996), Oatp2 (Noé et al., 1997), and Ntcp (Schroeder et al., 1998) expressed in the Xenopus laevis oocytes were around 4.5 to 27 μM, showing that transport is of high affinity. Transport of E₁S was defined by these sinusoidal transporters and passive diffusion and was found to be similar among perivenous (PV) and perportal (PP) rat hepatocytes (Tan et al., 1999).

The objective of this study was to highlight the importance of transport, metabolism, and zonal aspects to understand their interplay on the futile cycling of estrogens in intact hepatocytes and, ultimately, the whole organ. In this article, metabolic activities in subcellular fractions of enriched PP and PV rat hepatocytes were assessed and in turn related to cellular expressions of rat liver estrone sulfatase and estrone sulfotransferase. These in vitro metabolic parameters and previously obtained transport parameters on hepatocyte uptake (Tan et al., 1999) were then used to describe the futile cycling between E₁S and E₁ in intact cells when E₁S (1, 5, 25, and 125 μM) was incubated with PP and PV hepatocytes.

**Experimental Procedures**

**Materials.** [6,7-³H]E₁S (ammonium salt; specific activity, 53 Ci/mmol), [6,7-³H]E₂ (specific activity, 40.6 Ci/mmol), and [4–¹⁴C]E₂ (specific activity, 56.6 Ci/mmol) were purchased from NEN Life Science Products (Boston, MA). The radiochemical purities, as found by high-performance liquid chromatography (HPLC) or thin-layer chromatography, were greater than 95%. Unlabeled E₁, E₂, PAPS, and bovine serum albumin (fraction V) were purchased from Sigma Chemical Co. (St. Louis, MO). Collagenase was obtained from Collagenase Type I (0.25 U/mg; Sigma Chemical Co., St. Louis, MO). Dextran (molecular weight 200,000), non-fatty liver phospholipid (Naizolv, Nurolab, St. Louis, MO), digitonin, and goat serum albumin were purchased from Boehringer Mannheim (Oakville, ON, Canada). Goat anti-rabbit horseradish peroxidase conjugate was kindly provided by Dr. Charles N. Falany (University of Alabama, Birmingham, AL). The immunoblot Assay Kit (mini-Protein II systems) was obtained from Bio-Rad Laboratories (Mississauga, ON, Canada). Goat anti-rabbit horseradish peroxidase conjugate was obtained from Amersham Pharmacia Biotech (Oakville, ON, Canada). All other reagents were of the highest available grade.

**Isolation of Zonal Rat Hepatocytes, Lysates, and Subcellular Fractions of Zonal Hepatocytes.** Male Sprague-Dawley rats (275–325 g, Charles River Canada, St. Constant, QC, Canada) were used for the preparation of isolated hepatocytes. Rats were housed in accordance with Animal Protocols at the University of Toronto under a 12:12-h light:dark cycle and were given food and water ad libitum.

Enriched PP and PV hepatocytes were isolated by the digitonin/collagenase perfusion technique of Lindros and Penttila (1985), with modifications (Tan et al., 1999). Viability of the zonal hepatocytes was greater than 90%, as assessed by trypan blue exclusion. The enrichment of PP and PV cells was assessed by use of enzyme markers: alanine aminotransferase, which was measured by a Sigma diagnostics kit, and glutamine synthetase, which was assayed by a standard UV method (Meister, 1985). Cells were suspended in the incubation buffer consisting of NaCl (137 mM), KCl (5.4 mM), CaCl₂ (1 mM), MgCl₂·6H₂O (1 mM), MgSO₄·7H₂O (0.83 mM), NaH₂PO₄·2H₂O (0.5 mM), NaHPO₄·12H₂O (0.42 mM), NaHCO₃ (4.2 mM), glucose (5 mM), and HEPES (1 mM, pH 7.4). The 9000g supernatant (S9) and the 100,000g cytosolic fractions were obtained from zonal hepatocytes by homogenization (Ultra-Turrax T25 homogenizer, Janke & Kunkel, Staufen im Briesgau, Germany) and stepwise centrifugation at 9000g and 100,000g for 20 and 60 min, respectively, at 4°C.

Cell lysates from the most distal and proximal hepatocites of the sinusoid were prepared by the dual-digitonin-pulse perfusion technique according to Quistoför and Grunnet (1987), with modifications (Tirona et al., 1999). Rat livers were perfused with a perfusion buffer [Hank’s buffer (pH 7.2) containing 10 mM HEPES, 0.5 mM EGTA, 4.2 mM NaHCO₃, and 5 mM glucose].

**Estrone Sulfatase Activity.** Estrone sulfatase activity in the S9 of zonal hepatocytes was determined by formation of [³H]E₁ from [³H]E₁S. After preincubation of zonal S9 and E₁S separately at 37°C for 5 min, the solutions were combined to result in a mixture of S9 protein (1.4 mg) and E₁S (1–200 μM with 1–177 × 10⁵ dpm/μl of [³H]E₁S) in a final volume of 0.4 ml of Tris-HCl buffer (25 mM) at pH 7.4. Samples (0.1 ml) were then removed at 2 min, a predetermined time in which product formation was linear with time, into 0.5 ml of acetonitrile containing 4 μM danazol, the internal standard for HPLC analyses.

**E₁Sulfotransferase Activity.** Estrone sulfotransferase activities in the zonal lysates and cytosolic fractions were estimated from that rates of formation of [³H]E₁S from [³H]E₁. Lysates and cytosolic fractions of zonal hepatocytes, which were preincubated at 37°C for 5 min, were added to mixtures of PAPS, E₁, and [³H]E₁ (2.0 ± 0.1 × 10⁶ dpm/ml) to result in 1 μM E₁ and 700 μM PAPS in 1 ml of Tris-HCl buffer (25 mM) at pH 7.4. To ensure sufficient co-substrate for the reaction, the PAPS concentration chosen was higher than that reported for the rat liver (70 nmol/g of liver or 117 μM PAPS in cell water) (Brzeczniak et al., 1987). Samples (0.2 ml) were removed at 6 min, a predetermined time in which E₁ sulfation was linear with time. The samples were added to 0.8 ml of acetonitrile containing 4 μM danazol.

**Metabolism of E₁S in Intact Zonal Hepatocytes.** Zonal hepatocyte suspensions (2 × 10⁶ cells/ml, preincubated for 10 min at 37°C in the incubation buffer, were added to equivalents of unlabeled E₁S and [³H]E₁S (5.1 ± 0.3 × 10⁶ dpm/ml) prepared in incubation buffer to result in 1, 5, 25, and 125 μM E₁S in 10⁶ cells/ml. Two samples were retrieved at various times (1–30 min) from the incubation mixture. The first sample (100 μl) was deproteinized immediately with 0.4 ml of acetonitrile containing 4 μM danazol, and the second sample (150 μl) was placed immediately into a polystyrene microtube tube containing 4 μM danazol in 0.4 ml of acetonitrile. Subsequently, the contents of E₁ and E₁S in the incubation mixture and extracellular medium were assayed by HPLC. The amount of E₁S or E₁ in the cellular space was estimated by the difference of the quantities in the incubation mixture and extracellular medium. The difference in mass between the administered amount and the sum of E₁S and E₁ provided an estimate of the formation of other E₁ metabolites (M₂: estrone glucuronide or E₂G, estradiol (E₂), and its conjugates) at various times.

**Protein Binding/Metabolism in Extracellular Medium.** During the preparation of isolated hepatocytes, protein debris from suspending dead cells (0.16 ± 0.06 mg/10⁶ cells) was found to persist routinely in the incubation mixture despite the washings; centrifugation with percoll failed to remove the protein debris fragments. In view of the tight binding of E₁S and E₁ to albumin (Rosenthal et al., 1972; Rao, 1998), binding of E₁S and E₁ to the protein debris in the extracellular medium was estimated by ultrafiltration (Centricon 3, Amicon Inc., MA). Solutions containing [³H]E₁S (8.5 × 10⁵ dpm/ml) or [³H]E₁S (4.9 ± 2.4 × 10⁵ dpm/ml) plus E₁S (0.8–250 μM) were added to blank extracellular medium of the incubation mixture, which was prepared in the absence of drug. After incubation of the mixture for 10 min at 37°C, an aliquot (2 ml) was removed to a Centricon tube and centrifuged at 2500g for 20 min at 37°C. Liquid scintillation fluor (5 ml, Ready Safe, Beckman Coulter, Mississauga, ON, Canada) was added to the original mixture (0.2 ml) and the resulting filtrate (0.2 ml) in different micounting vials, then quantified by liquid scintillation spectrometry (model LS6800, Beckman Coulter). Leakage of protein through the Centricon filter was less than 0.5% of the mixture solution. Desulfation of E₁S and metabolism of E₁ within the extracellular medium were less than 1% over the experimental time and were deemed insignificant.

**Immunoblot Analysis.** Lysates, centrifuged at 100,000g for 60 min at 4°C, and the cytosolic fraction of zonal hepatocytes, prepared as described by Tirona et al. (1999), was used for immunoblot analysis. Aliquots containing 10 μg of protein were resolved by SDS-PAGE in a 12% polyacrylamide gel and electrophoretically transferred to nitrocellulose membrane. Primary rabbit an-
tibodies (anti-rSULT1A1 at 1:20,000, anti-rSULT2A1 at 1:10,000, and anti-rSULT1E1 at 1:20,000 dilution) were then incubated with the blots for 1 h at room temperature. Finally, goat anti-rabbit IgG horseradish peroxidase conjugate (1:40,000) was used as the secondary antibody, and the immunoreagents were detected by chemiluminescence (Amersham). The intensity of the protein band was integrated using the NIH Image software (http://rsb.info.nih.gov).

**Protein Assay.** In all preparations, protein was determined by the method of Lowry et al. (1951), with bovine serum albumin as the standard.

**HPLC Analysis.** Liquid chromatography was performed on a Shimadzu HPLC system (Shimadzu Corporation, Kyoto, Japan) equipped with a SCL-10A system controller, a SPD-10A-XL automatic injector, and a CR-4A chromatopac integrator. Separation was carried out by a 10-μm Bondapak C18 reversed-phase column (39 cm × 300-mm i.d.; Waters, Milford, MA). A binary gradient consisting of mobile phase A (10 mM ammonium acetate, pH 7.5) and mobile phase B (acetonitrile) was used at a constant flow rate of 1 ml/min for the separation of E1G, E1S, E1, E2, and danazol. Initially, the wavelength of detection was set at 270 nm for the detection of E1G and E1S, and the mobile phase was linearly increased from 10% B to 50% B in 15 min. Then the mobile phase was maintained at 50% B for 10 min, and the wavelength was altered to 285 nm at 20 min for the detection of E1 and E2. At 25 min, the mobile phase was linearly increased to 75% B in 2 min and was maintained for another 10 min before being brought back down to 10% B over the next 5 min. The mobile phase was maintained at 10% B for an additional 5 min to re-equilibrate the column. The retention times were as follows: E1G, 14 min; E1S, 16 min; E1, 24 min; E2, 26 min; and danazol, 34 min.

Good correspondence was observed between the eluted radioactivity ([3H]E1S and [3H]E1), which was collected at 0.5-min intervals after sample injection and UV absorbance. No carryover of radioactivity was observed for the compounds of interest despite a delay of 0.5 min between UV detection and radioassay. Therefore, the delay time was incorporated to the automated fraction collector (model 202, Gilson Medical Electronics, Middleton, WI). After the addition of 10 ml of Ready Safe (Beckman Coulter), the collected fractions were quantified by liquid scintillation spectrometry (model LS6800, Beckman Coulter).

**Kinetic Analysis for Extracellular Binding of E1S and E1.** The binding of E1S and E1 to proteins that were present in the extracellular medium was described by the Langmuir binding isotherm (eq. 1), where the bound concentration of extracellular E1S ([E1S bound]ec) was related to the unbound concentration ([E1S unbound]ec) by the binding dissociation constant, Kd,E1S, and the product of number of binding site (n,E1S) and the total protein concentration in the extracellular medium ([P total]ec). The kinetic constants were obtained by regression of [E1S bound]ec versus [E1S unbound]ec according to eq. 1 with use of the fitting software package SCIENTIST (version 2; MicroMath Scientific Software, Salt Lake City, UT) and an optimized weighting scheme (1/observation²):

\[
[E1S_{bound}]_{ec} = \frac{n_{E1S} [E1S_{unbound}]_{ec}}{K_d} + [E1S_{unbound}]_{ec} .
\]  

After obtaining Kd,E1S and n,E1S from eq. 1, eqs. 2 and 3 were used to estimate the tissue binding of E1S in the hepatocyte from known total protein concentration in cell-homogenate ([P total]c).

\[
E1S_{bound} = \frac{n_{E1S} [P_{total}]_{c}}{[P_{total}]_{ec}} .
\]  

\[
E1S_{bound} = \frac{n_{E1S} [P_{total}]_{c}}{[P_{total}]_{ec}} .
\]  

\[
E1S_{bound} = \frac{n_{E1S} [P_{total}]_{c}}{[P_{total}]_{ec}} + [E1S_{unbound}]_{ec} .
\]  

**Kinetic Modeling of E1S and E1 Disposition in Intact Zonal Hepatocytes.** A cellular kinetic model that considered protein binding in both extracellular and cellular spaces, transport, metabolism, interconversion, and an intracellular vesicular compartment (Fig. 1) best described the concentration-and time-dependent data of E1S and E1 in enriched PP and PV hepatocytes. Inclusion of binding in both cellular and extracellular medium is justified in view of the demonstrable binding but lack of metabolism in extracellular medium, which contained protein debris from cells. E1S binding and debinding to protein are denoted by on- and off-rate constants, k on,E1S and k off,E1S, respectively; these constants and the ratio Kd,E1S ([Kd,E1S] / Kd,E1) are expected to be identical for both extracellular and cell media. However, the protein concentration or [P total]ec in the extracellular medium is only a fraction of that in cells since the [P total]c is much higher. The effective binding concentration in cell was determined by multiplication of the ratio of protein concentrations in cell/ debris ([Ptotal]c / [Ptotal]ec) with n,E1S[Ptotal]c, according to eq. 2. For the sake of simplicity, the unbound concentration of E1S is represented by the product of the unbound fractions of E1S ([f on,E1S] and [f off,E1S] represent the unbound fraction of E1S in the cell and the extracellular medium, respectively) and the total concentration of E1S. Since the canalicular membrane on the cell surface that mediates excretion of anions is known to internalize to form vesicles shortly after hepatocyte isolation (Oude Elferink et al., 1993), a similar phenomenon was postulated to exist for E1S accumulation into vesicles. A vesicular compartment is included for E1S since E1S undergoes demonstrable biliary excretion in the perfused rat liver (Tan et al., 2001).

Previously obtained parameters on transport were scaled up and used in the fitting procedure. The transport parameters for E1S (V max,E1S and P diff,E1S) obtained from our previous hepatocyte uptake study (Tan et al., 1999) were
scaled up with the factor $\phi = 1.6$ mg of protein/10$^6$ cells; Mahler and Cordes, 1966; Liu et al., 1980). Based on these transport parameters of E$_S$ (Tan et al., 1999), the uptake of E$_S$ was mainly attributed to carrier-mediated transport, although the minor bidirectional flux of E$_S$ $(P_{\text{diff}}^{E_S})$ also contributed to E$_S$ transport. Because uptake of E$_S$ was too rapid for proper characterization of transport constants in hepatocyte uptake studies, the observed linear transport clearance for E$_S$, $P_{\text{tot}}^{E_S}$, is assumed to exist for the permeation of E$_S$ at all concentrations. The in vitro parameter for the desulfation of E$_S$ $(V_{\text{max}}^{E_S})$ and the linear sulfation intrinsic clearance of E$_S$ $(K_{\text{intrinsic}}^{E_S})$ were scaled up with factors $\alpha$ and $\beta$ ($\alpha = 0.8$ mg of S9 protein/10$^6$ cells; $\beta = 0.5$ mg of cytosolic protein/10$^6$ cells; Mahler and Cordes, 1966; Liu et al., 1980), respectively. It must be noted that the metabolic intrinsic clearance for estrone sulfation, $K_{\text{intrinsic}}^{E_S}$, could only be defined within a narrow concentration range of E$_S$ in vitro because of poor aqueous solubility, and this was used to relate $V_{\text{max}}^{E_S}$ to $K_{\text{intrinsic}}^{E_S}$ to the ratio $\frac{V_{\text{max}}^{E_S}}{K_{\text{intrinsic}}^{E_S}}$. Since E$_S$ is known to form other metabolites (M., denoting the mixture of E$_G$, estradiol, estriol, and other estrogen conjugates; Holzer et al., 1976), a simplified metabolic scheme (Fig. 1) was used to describe the formation of all M with the pooled metabolic constants, $V_{\text{max}}^{M}$ and $K_{\text{intrinsic}}^{M}$. The intrinsic clearance of E$_S$ entry into vesicles is denoted by $V_{\text{intrinsic}}^{E_S}$. The PP and PV cell volumes ($V_c$) were assumed to be 3.6 and 4.1 $\mu$l/10$^6$ cells, respectively (Garcia-Ruiz et al., 1994), and the extracellular volume ($V_e$) was obtained by the difference [total volume of the preparation (1 ml) $-$ $V_c$].

**Fitting.** Mass balanced rate equations (see Appendix) were written to describe events of the cellular kinetic model (Fig. 1). Fitting was performed by the software package SCIENTIST based on experimentally obtained binding, metabolic, and transport parameters (Table 1). The parameters—transport clearance of E$_S$ ($P_{\text{tot}}^{E_S}$), the Michaelis-Menten constant for uptake of E$_S$ into hepatocytes ($K_{\text{intrinsic}}^{E_S}$), the vesicular intrinsic clearance for accumulation of E$_S$ ($V_{\text{intrinsic}}^{E_S}$), the pooled kinetic constants for formation of the composite of E$_L$ metabolites M ($V_{\text{max}}^{M}$ and $K_{\text{intrinsic}}^{M}$), the kinetic constants for E$_S$ sulfation ($V_{\text{max}}^{E_S}$ and $K_{\text{intrinsic}}^{E_S}$), the latter constrained as $V_{\text{max}}^{E_S} = rSULT1A1 \cdot V_{\text{intrinsic}}^{E_S}$, and the tissue binding of E$_S$—were optimized by least-square fitting with appropriate weighting schemes of 1/observation (for data increasing in value) and 1/observation$^2$ (for data decreasing in value). The goodness of fit was viewed with respect to the coefficient of variation (standard deviation of parameter estimate/parameter value), the residual plot, and the Model Selection Criterion (MSC).

**Statistics.** All data were presented as the mean ± S.D., and the means were compared by use of ANOVA, with the $P$ value of 0.05 as the level of significance. A paired $t$ test was used to compare the means for the data on zonal lysates since the same liver was used for the preparation of both PP and PV lysates; the level of significance was set at 0.05.

**Results**

**Biochemical Characterization of Zonal Hepatocytes and Lysates.** The marker enzymes, alanine aminotransferase and glutamine synthetase, verified that enriched PP and PV hepatocytes and lysates were isolated from different acinar regions of the rat liver. The PP/PV ratios of the marker enzyme alanine aminotransferase for zonal hepatocytes and zonal lysates were 1.9 ± 0.9 and 7.4 ± 4.2, respectively. The acinar gradient of alanine aminotransferase content in zonal lysates was steeper because the preparations were obtained from the most distal and proximal acinar regions of the rat liver. However, the PP/PV ratios of the marker enzyme glutamine synthetase for the zonal hepatocytes and lysates were 0.027 ± 0.023 and 0.029 ± 0.013, respectively, and were similar. These PP/PV ratios were in agreement with those reported by others (Lindros and Penttilä, 1985; Quistorff and Grunnet, 1987; Tosh et al., 1996; Tirona et al., 1999).

**Desulfation of E$_S$ in the Zonal S9 Preparations.** Preliminary study failed to show E$_S$ sulfation in absence of PAPS within the zonal S9 preparations. Therefore, the rate of E$_S$ formation from E$_S$ in S9 represented the true desulfation rate. The results were best fit to the Michaelis-Menten equation (Table 1 and Fig. 2), yielding similar $K_{\text{intrinsic}}^{E_S}$ (30 to 34 $\mu$M) and $V_{\text{max}}^{E_S}$ (4.2–2.9 nmol/min/S9 protein) values for estrone desulfation in the PP and the PV preparations (ANOVA, $P > 0.05$). The $K_{\text{intrinsic}}^{E_S}$ was much lower in relation to that reported for another well studied sulfate conjugate, 4-methylumbelliferonyl sulfate (Chiba and Pang, 1993).

**E$_S$ Sulfation in Zonal Lysates and the Cytosol of Zonal Hepatocytes.** Estrone sulphotransferase activity was detected in zonal lysates and cytosolic fractions of PP and PV hepatocytes in the presence of PAPS. Desulfation of E$_S$ in zonal lysate and zonal cytosol was less than 1% over the experimental time and was negligible. Hence in both lysate and cytosol, the observations reflected the true and not the net sulfation activity of E$_S$ sulphotransferases. The activity was significantly higher in the PV region than the PP region (Table 2). The PV/PV ratios of estrone sulfation activities in the cytosolic fractions and lysates were 4.3 ± 2.2 and 3.1 ± 1.8, respectively.

**Immunoblot of rSULT1A1, rSULT2A1, and rSULT1E1 in Zonal Hepatocytes and Zonal Lysates.** The rSULT1E1 protein in the cytosolic fraction of PV hepatocytes was 3.4 ± 1.1 times that of PP and paralleled the results obtained previously for CYP1A2, a PV marker within the same cell preparations (PV/PV ratio of 4.1 ± 3.3; Tirona et al., 1999). On the other hand, the rSULT2A1 protein in PP hepatocytes was 3.5 ± 2.7 times that of the PV hepatocytes, and the rSULT1A1 protein was not significantly different (ANOVA, $P > 0.05$; PV/PV ratio of 1.13 ± 0.23) among zonal hepatocytes (Fig. 3). Trends for the zonal lysates remained similar to those of the zonal hepatocytes: the rSULT1E1 protein in the PV lysates was 4.0 ± 3.0 times that of the PP lysates. The rSULT2A1 protein was exclusively found in the PP lysates, and the rSULT1A1 protein was again present evenly among zonal lysates (Fig. 4).

**Protein Binding of E$_S$ and E$_L$.** The binding data of E$_S$ (0.8–250 $\mu$M) in extracellular medium were best described by the Langmuir binding isotherm (eq. 1). Assuming that the molecular mass of binding proteins were around 82 kDa (the molecular mass of estrogen binding protein; Rao, 1998), the $n^{dE}[P_{\text{total}}]_{\text{ec}}$ and the $K_{D}^{E_S}$ for E$_S$
TABLE 2

Sulfation of tracer [\( ^{3}H \)]E1 in the cytosol fraction of zonal hepatocytes (n = 4) and zonal lysates (n = 4) in the presence of the cosubstrate PAPS (700 \( \mu M \)).

<table>
<thead>
<tr>
<th></th>
<th>Sulfation Intrinsic Clearance of Estrone (( \mu M/\text{min/mg protein} ))</th>
<th>PP/PV Ratio</th>
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<tbody>
<tr>
<td>Zonal Hepatocytes</td>
<td></td>
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</tr>
<tr>
<td>PP</td>
<td>6.1 ( \pm ) 2.2</td>
<td>0.23</td>
</tr>
<tr>
<td>PV</td>
<td>26.4 ( \pm ) 9.5*</td>
<td></td>
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<tr>
<td>Zonal Lysates</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Periportal (LP)</td>
<td>8.3 ( \pm ) 4.3</td>
<td>0.32</td>
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<tr>
<td>Perivenous (LV)</td>
<td>25.9 ( \pm ) 6.8**</td>
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* Statistically significant from periportal (ANOVA, \( P < 0.05 \)).
** Statistically significant from periportal (paired \( t \) test, \( P < 0.05 \)).

Metabolism of E1,S in Intact Zonal Hepatocytes. Concentration-dependent metabolism of E1,S was observed in intact PP and PV hepatocytes (Fig. 6A). For both PP and PV hepatocyte preparations, biphasic elimination patterns were observed for the lower concentrations of E1,S (\(<25 \mu M\)) whereas monoexponential decay profiles were observed at the highest concentration of E1,S used (125 \( \mu M \)). The patterns of E1,S in extracellular medium paralleled those in the incubation mixture (Fig. 6B) and were similar for both PP and PV cells. However, the pattern differed dramatically in the cell wherein cellular concentrations of E1,S were much higher than those extracellularly (Fig. 6C), yielding apparent tissue to medium partitioning ratios of greater than unity in both PP and PV cells (Fig. 7A). The apparent partition coefficients of E1,S at equilibrium decreased with increasing E1,S concentration and were similar for both PP and PV cells (Fig. 7B). As shown in Table 3, nonlinear kinetics were shown to exist with increasing E1,S doses. Values of the AUC of E1,S were higher in PP than in PV hepatocytes, although statistical significance was not found (Table 3). The apparent clearance of E1,S \([\text{dose/\text{AUC}_{\text{PP}}(0 \rightarrow \infty)}]\) decreased with increasing dose and was lower in PP hepatocytes than in PV hepatocytes. Again, statistical difference was not found due to the large interanimal variability.

Patterns of E1 in the extracellular medium (Fig. 6E) and incubation mixture (Fig. 6D) were similar to those for the cell (Fig. 6F), but the decay of E1 was faster than that of E1,S (Fig. 6). The terminal half-lives of E1 differed for each dose (compare Fig. 6C with 6F). At the lower initial concentrations of E1,S used for incubation with hepatocytes, greater E1 levels existed in PP hepatocytes than in PV hepatocytes. Values of the AUC of E1 were higher in PP than in PV.
hepatocytes, and statistical significance was found for $\text{AUC}_{E1S}^{SC}(0 \rightarrow 30 \text{ min})$ for the lower concentrations of $E1S$ used for this study (Table 3). At higher initial concentrations of $E1S$ ($>5 \mu M$), the decay half-life of $E1$ in the cell was more prolonged, suggesting that the enzymes for the metabolism of estrone had become saturated.

**Fitted Results for $E1S$ and $E1$ in Intact Zonal Hepatocytes with the Kinetic Model.** When simultaneous fitting was performed on the total, extracellular, and cellular $E1S$ and $E1$ data for each set of experiments consisting of four $E1S$ initial concentrations and the same pool of hepatocytes, good fits were obtained, although high coefficients of variation were found associated with the fitted parameters. The optimized fit that considered tissue binding and vesicular storage of $E1S$ is presented in Fig. 6, and the mean of the optimized parameters of five experiments and the assigned parameters are summarized in Table 4.

The uptake constant of $E1S$, $K_{\text{uptake}}^{E1S}$, when optimized (10–12 $\mu M$), was only half of the in vitro value (24 $\mu M$), showing that the hepatocyte uptake clearance (if $E1S_{\text{uptake}}^{\text{max}} = 246–282$ $\mu M/\text{min}/10^6$ cells or 31–35 ml/min/g of liver; Table 5), although of high value under first-order conditions, was readily saturated. The hepatocyte uptake clearance for $E1$ that is assumed to mediate bidirectional transport was even faster (1463–1484 $\mu M/\text{min}/10^6$ cells). These values suggest that under first-order conditions, transport of the estrogenic compounds are flow-rate limited in the rat liver.

The $V_{\text{max}}^{E1S}$ for estrone sulfation was low, differing in both PP and PV cells (0.014–0.077 nmol/min/10^6 cells), but the $K_{\text{m}}^{E1S}$ was of high affinity (4–6 $\mu M$) and was similar in PP and PV cells. These values suggest that estrone sulfation, when compared with estrone sulfate desulfation, is a high-affinity but low-capacity pathway that would rapidly become saturated. By constraining the $K_{\text{m}}^{E1S}$ as $C_{\text{int}}^{E1S}/V_{\text{max}}^{E1S}$, we optimized the $V_{\text{max}}^{E1S}$ value; the converse procedure of constraining the $V_{\text{max}}^{E1S}$ as $C_{\text{int}}^{E1S}/K_{\text{m}}^{E1S}$ resulted in a higher coefficient of variation for the estimate of $K_{\text{m}}^{E1S}$. The $V_{\text{max}}^{E1}$ and $K_{\text{m}}^{E1}$ values for formation of other metabolites, M, were 5.9 to 9.4 nmol/min/10^6 cells and 18 to 19 $\mu M$, respectively, in PP and PV cells, showing that formation of other estrone metabolites greatly exceeds that of $E1S$ and exhibits a greater PV abundance.

These fitted results indicate that both the sulfation of $E1$ and the formation of M in PV hepatocytes are significantly higher than those in PP hepatocytes (Tables 4 and 5). The fitted tissue unbound fraction for $E1$ was low (0.025–0.03) and was likely due to the presence of the estrogen binding protein in hepatocytes (Rao, 1998).

The inclusion of the vesicular compartment in modeling seemed to be justified since cellular accumulation of $E1S$ followed by only a gradual depletion of $E1S$ was observed. Indeed, absence of the cellular storage compartment of $E1S$ provided a slightly inferior fit, predicting a slightly faster decay of $E1S$ and greater formation of $E1$ in the liver cell. The contents of $E1S$ and $E1$ in the extracellular and total medium were, however, affected only slightly (data not shown), since the total accumulation of $E1S$ in the vesicular space at 30 min amounted to only 2% of the dose. By contrast, the binding of $E1S$ in debris and in tissue was found to be of paramount importance. Absence of binding resulted in very poor fits that predicted monoeXponential decay rate constants for $E1S$ in the extracellular medium, and the accumulation of $E1S$ in the cell at early time points (Fig. 6C) was greatly attenuated in the absence of binding (data not shown). The accumulation pattern of $E1S$ in cell is therefore attributed mostly to tissue binding and less to vesicular storage.

**Discussion**

Estrone sulfate plays a vital role in the cycling of estrogens. Being hydrophilic, $E1S$ serves as a mobile estrogen and allows easy delivery to target tissues. $E1S$, a common substrate of Oatp1, Oatp2, Oatp4, Ntcp, and OAT3, gains ready access into the liver tissue where it is transported and binding activities to examine the influence of metabolic heterogeneity on the futile cycling of estrogens in intact zonal hepatocytes. Notably, in contrast to parallel decay profiles in both extra-cellular medium for both parent and metabolite (Ebling and Jusko, 1986), we observed different decay half-lives for $E1S$ and $E1$ in the hepatocyte system (Fig. 6).

From in vitro values of the kinetic constants for $E1S$ desulfation ($K^{E1S\rightarrow E1}_{\text{m}}$ 30 and 35 $\mu M$ and $V^{E1S\rightarrow E1}_{\text{max}}$ values of 2.2 and 1.9 nmol/min/10^6 cells, respectively, for PP and PV hepatocytes), there was no difference in metabolic activity for both the proximal and distal regions of the rat liver. The observation was in good agreement...
with other findings on the homogeneous distribution of arylsulfatase C activity (Anundi et al., 1986). The $K_m$ values were similar to that of a previous study ($32 \mu M$; Iwamori et al., 1976). By contrast, estrone sulfation was of higher affinity ($K_m$ of 4.4–5.9 $\mu M$) in both PP and PV regions, but the $V_{\text{max}}^{E_1\rightarrow E_1-S}$ was much lower in value and differed between PP and PV hepatocytes (0.014–0.077 nmol/min/10^6 cells, respectively; Table 4). The observation was consistent with the trends on sulfation of tracer estrone in both hepatocytes and lysates (Table 2) as well as with immunoblot analyses of rSULT1E1 (Figs. 3 and 4). The PP/PV ratio of rSULT1E1 protein was consistent with those reported by others (Tosh et al., 1996). But the low PV/PP ratio of rSULT2A1 was opposite to the observation on sulfation activities, suggesting that hydroxysteroid sulfotransferase contributes little to estrone sulfation. The even distribution of rSULT1A1 protein in the zonal cells also indicates that phenol sulfotransferase only plays a minor role in estrone sulfation. This evidence confirms that sulfation of estrone is predominantly catalyzed by estrogen sulfotransferase (rSULT1E1) in the presence of PAPS.

The $CL_{\text{int}}^{E_1\rightarrow E_1-S}$ was about 4 to 23 times higher than the $CL_{\text{int}}^{E_1\rightarrow E_1}$ (Table 5), and $E_1$ sulfation was the rate-limiting step in the futile cycling. In addition to $E_1$ sulfation, $E_1$ was metabolized to $M$ with a much higher intrinsic clearance ($CL_{\text{int}}^{E_1\rightarrow M}$, 328 and 495 $\mu l/min/10^6$ cells, respectively; Fig. 6).
cells, respectively, for PP and PV cells; Table 5) that showed a PV preponderance. The competitive metabolism of E1 represents both glucuronidation by the UDP-glucuronosyltransferases that are localized pericentrally (Tosh and Burchill, 1996) and oxidation of E1 by CYP1A2 and -3A that are concentrated in the PV region (Oinonen et al., 1996). This “pooled” $\text{CL}_{\text{int}}$ was 38 to 106 times higher than the $\text{CL}_{\text{int}}$ for E1. Consequently, little E4 is resulfated back to form E1S. The higher activities for E1 sulfation and formation of M in the PV region translates to the higher accumulation of E1 in PP cells, as observed under low concentrations (cf. AUC values in Table 3).

Upon comparison of the metabolic intrinsic clearances of E1 sulfation and E1S desulfation to those for transport, the hepatic uptake clearances greatly exceed the metabolic intrinsic clearances (Table 5). The transport clearance of E1S is rapid, but that for E1 is even faster. The CL$_{\text{uptake}}$ (Table 5) is still higher. Under physiological and first-order conditions where both E1 and E1S exist in low concentrations (nM), transport should remain very rapid and unsaturated. At high concentrations of E1S, however, transport may become saturated at concentrations comparable with or exceeding $K_m^{E1S}$. The value of the fitted $K_m^{E1S}$ is within the range of the $K_m$ values (4.5–27 $\mu$M) reported for the various transporters and was similar to the value of $K_m^{E1}$ (24 $\mu$M) obtained in vitro (Tan et al., 1999). Adoption of the in vitro $K_m^{E1S}$ value (24 $\mu$M), however, provided poorer fits. We found that the parameters for the transport systems of E1S obtained from fitting were similar for both PP and PV hepatocytes, and the finding suggests the uniform distribution of transporters in rat liver. Uniform acinar distributions were found for Ntcp (Stieger et al., 2000), Oatp1 (Abuzahra et al., 2000), and Oatp2 (Tirona et al., 2000) in rat liver, and uptake of E1S was similar in zonal hepatocytes (Tan et al., 1999). Saturation in uptake had occurred within the concentration range studied in the hepatocyte system, and this was shown by the decreasing partition coefficients of E1S with increasing concentrations (Fig. 7B). Consistent with lack of zonation in uptake, values of the equilibrium partition coefficients of E1S were similar for both PP and PV hepatocytes.

Although previous evidence has suggested that transport of E1 across the membrane might involve carriers (Rao et al., 1977), our data were consistent with a linear, transmembrane flux for E1 (P$_b^{E1}$). The bidirectional uptake clearance for E1 (1463–1484 $\mu$M/min/10$^6$ cells) was even faster than that for E1S, and no difference was found among PP and PV hepatocytes. The rapid transport clearance of E1 was congruent with parallel trends of E1 in cellular and extracellular

![Fig. 7. Partitioning of E1S between cell and medium in PP and PV hepatocyte systems.](image)

A, time-dependent profiles for the partition coefficients of E1S, cellular concentration/extracellular concentration, in relation to the different initial concentrations of E1S [1 (■), 5 (○), 25 (▲), and 125 $\mu$M (●); mean ± S.D.], and the corresponding open symbols represent the PV data. B, a decreasing pattern of the partition coefficients of E1S existed at equilibrium for the various initial concentrations of E1S (1–125 $\mu$M).

**TABLE 3**

<table>
<thead>
<tr>
<th>E1S $\mu$M</th>
<th>Cellularb</th>
<th>AUC of E1S</th>
<th>Extracellularb</th>
<th>AUC of E1</th>
<th>Extracellularb</th>
<th>CL$_{\text{app}}$ of E1S</th>
<th>AUC of E1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AUC$_{\text{EC}}$(0 → 30 min)</td>
<td>AUC$_{\text{EC}}$(0 → 30 min)</td>
<td>AUC$_{\text{EC}}$(0 → 30 min)</td>
<td>AUC$_{\text{EC}}$(0 → 30 min)</td>
<td>AUC$_{\text{EC}}$(0 → 30 min)</td>
<td>AUC$_{\text{EC}}$(0 → 30 min)</td>
<td>AUC$_{\text{EC}}$(0 → 30 min)</td>
</tr>
<tr>
<td>PP 1</td>
<td>74 ± 31</td>
<td>2.6 ± 0.9</td>
<td>3.0 ± 1.1</td>
<td>0.34 ± 0.12</td>
<td>0.34 ± 0.12</td>
<td>60 ± 27</td>
<td>0.71 ± 0.24</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>560 ± 147</td>
<td>18 ± 3.3</td>
<td>20 ± 3.9</td>
<td>0.25 ± 0.05</td>
<td>300 ± 152</td>
<td>6.2 ± 1.7</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>3,668 ± 1,123</td>
<td>215 ± 27</td>
<td>236 ± 30</td>
<td>0.10 ± 0.014</td>
<td>2,052 ± 1,738</td>
<td>57 ± 14</td>
</tr>
<tr>
<td></td>
<td>125</td>
<td>18,704 ± 7,102</td>
<td>2,372 ± 325</td>
<td>2,634 ± 365</td>
<td>0.047 ± 0.007</td>
<td>5,363 ± 2,272</td>
<td>179 ± 79</td>
</tr>
<tr>
<td>PV 1</td>
<td>61 ± 14</td>
<td>2.5 ± 1.4</td>
<td>2.7 ± 1.6</td>
<td>0.37 ± 0.21</td>
<td>0.37 ± 0.21</td>
<td>42 ± 29</td>
<td>0.35 ± 0.10*</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>432 ± 161</td>
<td>17 ± 8.2</td>
<td>19 ± 9.1</td>
<td>0.26 ± 0.12</td>
<td>222 ± 113</td>
<td>3.7 ± 0.94*</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>3,366 ± 1,340</td>
<td>212 ± 75</td>
<td>227 ± 81</td>
<td>0.11 ± 0.04</td>
<td>1,755 ± 1,208</td>
<td>42 ± 15</td>
</tr>
<tr>
<td></td>
<td>125</td>
<td>18,908 ± 4,489</td>
<td>2,363 ± 322</td>
<td>2,586 ± 364</td>
<td>0.048 ± 0.007</td>
<td>5,166 ± 2,400</td>
<td>174 ± 45</td>
</tr>
</tbody>
</table>

* Statistically different from portal data (ANOVA, P < 0.05).

$^a$ CL$_{\text{app}}$ = [dose/AUC$_{\text{EC}}$(0 → 30 min)].

$^b$ AUC of 0 to 30 min, estimated by trapezoidal method.

$^c$ AUC of 0 to minute; the AUC up to 30 min was estimated using trapezoidal method, and this was added to C$_{\text{inf}}$/k (concentration at 30 min divided by the first order decay constant, k), assuming log-linear decline.
medium that suggest rapid equilibration (Fig. 6, E and F). The high $P_{\text{diff}}^e$ is probably due to the high lipophilicity of $E_1$; indeed, the octanol/water log $P$ value of $E_1$ is 3.1 (Howard and Meylan, 1997).

This study is the first account on binding of substrates to cell debris that resulted during hepatocyte preparation. The presence of extracellular binding of $E_1 S$ and $E_1$ has led to the conclusion that an even tighter tissue binding exists (Fig. 5B). Extracellular binding would decrease the uptake of $E_1 S$ and $E_1$, whereas cellular binding of $E_1 S$ and $E_1$ entraps the species within the cell and impedes cellular elimination. Tissue binding of $E_1 S$ and $E_1$ therefore exerts an important influence on the cellular kinetics of futile cycling of estrogens. Another issue that needs to be addressed with respect to tissue binding and metabolism is nonlinear tissue binding of $E_1 S$ and $K_{\text{m}}^\text{E1S} < K_{\text{m}}^\text{E1}$ ($24 \text{ vs. } 30–34 \mu M$). The comparison of $K_{\text{m}}$ values suggests that, with increasing cellular concentrations of $E_1 S$, saturation of tissue binding precedes the saturation of the metabolic enzymes for desulfation. A similar scenario—with $K_{\text{m}}$ for vascular binding of a flow-limited substrate $< K_{\text{m}}$—had resulted in nonlinearity in drug clearance (Chiba and Pang, 1993; Xu et al., 1993). The same consequence will result here with nonlinearity in tissue binding.

To understand the interplay among the nonlinearity in transport, tissue binding, and the presence of vesicular accumulation of $E_1 S$ on the different $t_{1/2}$ values of $E_1 S$ and of $E_1$, simulations were further performed with the fitted parameters, with the substitution a single, nonsaturable uptake clearance of $E_1 S$ ($CL_{\text{uptake}}^\text{E1S} = 246 \mu l/min/10^6$ cells), then a $10 \times$ higher dissociation binding constant ($K_{\text{D1S}}^\text{S}$ was increased to $230 \mu M$), and ultimately an absence of vesicular accumulation of $E_1 S$. When only linear transport was introduced, linear decay of extracellular $E_1 S$ was observed. But the difference in $t_{1/2}$ values of $E_1 S$ and $E_1$ persisted (data not shown). The similarity in decay $t_{1/2}$ values of $E_1 S$ and $E_1$ persisted (data not shown). The similarity in decay $t_{1/2}$ values of $E_1 S$ and $E_1$ persisted (data not shown). The similarity in decay $t_{1/2}$ values of $E_1 S$ and $E_1$ persisted (data not shown).
half-lives were attained for both drug and metabolite species, as expected of the futile cycling phenomenon (Fig. 8). The pattern conforms to other reversible metabolic systems that describe the futile cycling between methylprednisolone and methylprednisone for which similar in vivo elimination half-lives were observed for both drug and metabolite (Ebling and Jusko, 1986). It may be thus concluded that the nonlinearity in uptake and tissue binding, and the presence of vesicular accumulation of E1S, had resulted in different decay half-lives for E1S and E1 in the hepatocyte system.

In conclusion, both E1 and E1S are rapidly taken up evenly into rat zonal hepatocytes. The sulfation of E1 by estrogen sulfotransferase and the metabolism of estrone to other metabolites were more abundant in PV than in PP hepatocytes, although the desulfation of E1S was evenly distributed. The rate-limiting factor for the futile cycling of E1S and E1 was sulfation, since transport was rapid and the intrinsic clearance of E1S desulfation was higher than that of E1 sulfation. The higher levels of E1 and E1S in PP hepatocytes were due to the higher PV metabolic activity towards E1 sulfation and the formation of other metabolites. Different decay half-lives for E1 and E1S were observed, which were attributable to nonlinear uptake, tissue binding, and vesicular uptake of E1S in the cell.

Fig. 8. Simulated profiles of E1S and E1 in the hepatocyte incubation system.
A cellular kinetic model was presented (Fig. 1). \([E_1S], [E_1], [M]\), and \([P]\) denote the concentrations of \(E_1S, E_1\), metabolites of \(E_1\) other than \(E_1S\), and protein in various compartments; subscripts \(ec, c,\) and \(ves\) represent the extracellular medium, the cellular space, and vesicular compartment, respectively. Parameters were described in Table 3 and under Experimental Procedures.

The equations describing extracellular space (\(ec\)) for \(E_1\) and \(E_1S\) are as follows:

\[
\frac{d[E_1S_{unbound, ec}]}{dt} = \left( \left( \frac{V_{E_1S_{max}}}{m_{E_1S} + [E_1S_{unbound, ec}]} + p_{diff}^{E_1S} \right) [E_1S_{unbound, ec}] \right) V_{ec} \nonumber \\
- \left( \frac{V_{E_1S_{max}}}{m_{E_1S} + [E_1S_{unbound, ec}]} + p_{diff}^{E_1S} \right) [E_1S_{unbound, ec}] + k_{off}^{E_1S} [P_{unbound, ec}] [E_1S_{unbound, ec}] / V_{ec} \tag{A1}
\]

The total concentration of extracellular \(E_1S\) is the sum of unbound and bound \(E_1S\) and is given by

\[
\frac{d[E_{1, total, ec}]}{dt} = [P_{total}^{E_1S}]_{ec} - [P_{total}^{E_1S}]_{ec} / V_{ec} \tag{A3}
\]

The equation describing the amount of \(E_1S\) (\(E_1S_{ves}\)) effluxed into the vesicular space (\(ves\)) is

\[
\frac{dE_{1S_{ves}}}{dt} = C_{P_{diff}}^{E_1S} [E_1S_{unbound, ec}] \tag{A4}
\]

The equations describing cellular space (\(c\)) for \(E_1, E_1S,\) and \(M\) are as follows:

\[
\frac{d[E_1S_{unbound, c}]}{dt} = \left( \left( \frac{V_{E_1S_{max}}}{m_{E_1S} + [E_1S_{unbound, c}]} + p_{diff}^{E_1S} \right) [E_1S_{unbound, c}] \right) \frac{V_{ec}}{K_{m}^{E_1S}} + k_{off}^{E_1S} [P_{unbound, c}] [E_1S_{unbound, c}] \right) / V_{ec} \tag{A5}
\]

The total amount of intracellular \(E_1S\) is the sum of unbound, bound, and vesicular contents of \(E_1S\), and the total concentration of intracellular \(E_1S\) is obtained by dividing the total amount of intracellular \(E_1S\) by the cellular volume.

\[
\frac{d[E_{1, total, c}]}{dt} = \left( \left( \frac{V_{E_1S_{max}}}{m_{E_1S} + [E_1S_{unbound, c}]} + p_{diff}^{E_1S} \right) [E_1S_{unbound, c}] \right) \frac{V_{ec}}{K_{m}^{E_1S}} + k_{off}^{E_1S} [P_{unbound, c}] [E_1S_{unbound, c}] \right) / V_{ec} \tag{A7}
\]

The total intracellular concentration of \(M\) formed from estrone metabolism is

\[
\frac{d[M]}{dt} = \frac{\left( \frac{V_{E_1S_{max}}}{m_{E_1S} + [E_1S_{unbound, c}]} + p_{diff}^{E_1S} \right) [E_1S_{unbound, c}]}{V_{ec}} \tag{A8}
\]

The metabolic intrinsic clearance for desulfation is

\[
C_{P_{diff}}^{E_1S} = \frac{V_{E_1S_{max}}}{K_{m}^{E_1S}} \tag{A9}
\]

Binding of \(E_1S\) in extracellular medium is described by the binding capacity \((n_{E_1S}^{B}) \) [P_{total}^{E_1S}]_{ec} (where \(n_{E_1S}^{B}\) is the number of binding sites and \(P_{total}^{E_1S}\) is the total protein concentration in the extracellular medium) and the binding dissociation constant \((K_{D_1S}^{E_1S})\) as described below. We assumed that the cellular and the extracellular binding proteins have the same \(n_{E_1S}^{B}\) and \(K_{D_1S}^{E_1S}\). Thus, the binding capacity of cellular \(E_1S\) is obtained by multiplying the ratio of protein concentrations \((P_{total}^{E_1S})_{ec} / (P_{total}^{E_1S})_{ves}\) with the binding capacity \((n_{E_1S}^{B} P_{total}^{E_1S})_{ves}\).

\[
[P_{total}] = [P_{bound}] + [P_{unbound}] \tag{A10}
\]

The binding dissociation constant \(K_{D_1S}^{E_1S}\) is the ratio of the on and off rate constants for binding.

\[
K_{D_1S}^{E_1S} = \frac{k_{off}^{E_1S}}{k_{on}^{E_1S}} \tag{A11}
\]

Acknowledgments. We thank Dr. Charles N. Falany (University of Alabama, Birmingham, AL) for providing us with antibodies to rSULT1A1, rSULT2A1, and rSULT1E1. The assistance of Dr. Rommel G. Tirona in preparing zonal hepatocytes and lysates is gratefully acknowledged.

References


